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# CASCADE OF UNCERTAINTIES IN FLOOD DAMAGE ESTIMATIONS

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**ABSTRACT**: The quantification of flood risk involves several modelling steps each of which comprises uncertainties. This work compares the impact of different sources of epistemic uncertainty in potential flood damage estimates. We distinguish the uncertainties linked to models, methods and data, i.e. model uncertainties; and the uncertainties correlated with the hypotheses and choices to be introduced in the models, i.e. parametric uncertainties. In order to measure the global uncertainty of damage estimations, different data acquisition and modelling strategies were proposed for the four fundamental modules of the assessment: (1) hydrological analyses and considerations for determining discharges for different event probabilities; (2) the types of hydraulic model built and considerations when integrating topographical and bathymetric data; (3) the datasets and methods used to characterise the vulnerability of buildings to floods; and (4) the damage functions used and the errors related to characterising the value of the stakes. We propagate uncertainties linked to different strategies in the assessment results (sensitivity tests related to each assessment module) and we measured the results variability generated. The method was applied to two case studies in the French part of the Rhine River basin. The results of this analysis showed that the uncertainty of each module of the assessment depends on several factors that are highly dependent on the characteristics of the sites studied. However, the role played by flood hazard modelling was preponderant in assessing flood risk to buildings, especially for the most frequent floods. This showed that great attention must be given when modelling frequent floods for damage assessment purposes. The results of this study highlighted that the uncertainty linked to protection structures (dikes and dams) is a significant source of uncertainty in the damage assessment process.

Key Words: Flood loss, hydraulics, vulnerability, hydrology, sensibility analysis.

## 1. INTRODUCTION

Several recent studies have focused on the analysis of uncertainties linked to flood damage estimations. However, few studies have dealt comparatively with the impact of all the assessment strategies on the global result of these estimations (Merz et al., 2010b). Apel et al. (2008a) compared the impact of the selection of hydraulic models and damage models (damage functions) used when carrying out risk assessments. The authors insisted on the importance of quantifying the uncertainties of the different flood risk assessment modules, in order to gain better understanding of the compensation of uncertainties. They noted the considerable importance of the damage model in the final uncertainty of damage estimations. Contrary to Apel et al. (2008a), Merz and Thieken (2009) reached a different conclusion, that is to say that the damage model contributes little to the global uncertainty of damage assessments in comparison to uncertainties linked to hydrological and hydraulic models. Other studies have concluded that hydrological uncertainties and damage models are major sources of uncertainty in this type of estimation (de Blois and Wind, 1995). Obtaining better understanding and the reducing the uncertainties linked to damage assessments remain a real challenge for research. Resources availability as well as the size of the area of study are all decisive factors regarding the tools to be implemented, and thus elements crucial for the precision of the analyses (Messner et al., 2007). To reduce the uncertainties of these assessments efficiently, it is essential to determine the importance of the different sources of uncertainties in the process (de Blois and Wind, 1995). As mentioned by Green et al. (2011), appreciating the gains regarding the accuracy of the results in essential for risk management. The objective of this work is to compare the impact of the different sources of epistemic uncertainties in estimations of potential flood damage. In the first part of this work, we present the propagation of uncertainty method used to measure the part of the uncertainties related to different assessment modules. In the second part, we analyse the impact of the different assessment modules on estimates of direct damage to buildings in two case studies in France. This work is part of the thesis of Eleutério (2012).

## 2. METHOD

This study focuses on the epistemic uncertainties existing in different models required to assess flood damage. Merz and Thieken (2009) suggested that using several methods for analysing the same problem introduces the notion of epistemic uncertainty. We adopt this notion, by distinguishing the uncertainties linked to models, methods and data, *i.e.* model uncertainties; and the uncertainties correlated with the hypotheses and choices to be introduced in the models, *i.e.* parametric uncertainties (NRC, 2000). The uncertainty analysis method proposed here considers damage assessment as a classical deterministic process that comprises two major groups of variables that must be combined to obtain results. The "hazard" part of the assessment includes the hydrological analysis and hydraulic models necessary to understand flood hazard. The "stakes" part includes the assessment of the vulnerability and susceptibility of assets to suffer damage. In order to measure the global uncertainty of the damage estimation, different data acquisition and modelling strategies are proposed for the four fundamental modules of the assessment (Figure 1). The uncertainty analysis method proposed above (Figure 1) is composed of three steps: (1) the definition and implementation of several "strategies" for producing the different datasets required to assess potential damage (data related to flood hazard, the asset vulnerability and its susceptibility to damage); (2) the propagation of uncertainties linked to different strategies in the assessment results (sensitivity tests related to each assessment module); and (3) the quantification of the results variability generated by the different assessment scenarios and strategies. The method in question was applied to two case studies to better understand the influence of local characteristics on the mechanisms of uncertainties propagation linked to different damage assessment modules. The subjects of this study were the municipality of Holtzheim in the lower valley of the Bruche River and the municipality of Fislis in the upper valley of the Ill River, both located in the Rhine River basin.

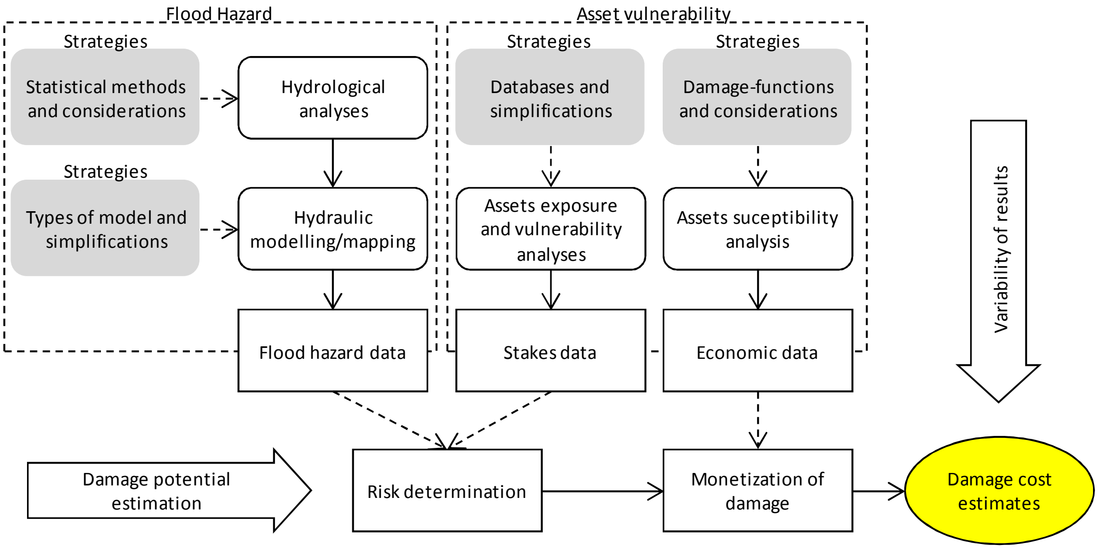

Figure 1: Diagram of the propagation of epistemic uncertainties of the different damage assessment modules.

## 2.1 Definition of evaluation strategies

The tests performed in this work were based on two strategic differentiation criteria concerning the assessment of potential flood damage: (1) the selection of models, methods, data and correlated uncertainties; and (2) the choice of assessment scales to model flood hazard and to assess the vulnerability of assets.

- Models, methods and data: In the methodology described in Figure 1, we determine a global configuration for the selection of models and hypotheses, taken as “reference”. The “reference” assessment is composed of a single model and a set of hypotheses for each assessment module, *i.e.* a hydrological model, a hydraulic model, a vulnerability model, and a damage model. This assessment comprises the most detailed description of the “hydraulic” and “vulnerability” modules. The other scenarios proposed conserve both the reference structure for three of the assessment modules, whereas the fourth module is subject to different choices: on the one hand, models, methods and data (which reveal the models uncertainties); and, on the other hand, considerations and simplifications in the parameterisation of the models (which reveal parametric uncertainties).

- Scales of assessment: Different global approaches are taken regarding the analysis scales of the two sections of the flood damage assessment, *i.e.* vulnerability of the stakes and the flood hazard. Three levels of scale are considered in the definition of these assessment scenarios: “micro” scale, “meso” scale and “macro” scale (Table 1).

Table 1: Scales for assessing flood hazards and the vulnerability of assets.

| Scale | Assets vulnerability | Flood hazard |
|---|---|---|
| MICRO | The characterisation of the assets is performed at the elementary scale (each building, infrastructure, object, etc.). Attention is given to the details of construction and occupation of each stake, for determining their material vulnerability. | Efficient hydrodynamic models are used with a detailed description of flows in river main channels and floodplains, by taking into account the particularities of existing hydraulic structures. Attention is given to the hydraulic characteristics of frequent and extreme floods. |
| MESO | The assets assessment is performed at the scale of homogenous blocks of land use (residential, industrial, commercial areas, etc.). Attention is given to the construction characteristics of stakes presenting a similar occupation. Aggregations of values are required. | Hydrodynamic models take into account rough description of flows in the river main channels with a relatively detailed description of the flood plain, without taking into account the detail of the analysis. Attention is given to events of all frequencies, with emphasis on the areas flooded by exceptional events. |
| MACRO | The assessment of assets is performed at the scale of administrative bodies (municipalities, departments, regions, nations, etc.). Attention is above all given to land use characteristics, omitting the characteristics of constructions. | The hydrodynamic modelling gives an approximate description of what occurs in the river main channel and floodplain, with attention mostly being given to the area flooded by exceptional events. |

## 2.2 Implementation of the different assessment strategies

### 2.2.1 “Hydrological” module: determination of event frequencies

We used a series of measurements over 39 years for the case study of the municipality of Holtzheim, and a series of measurements of the river Ill over 30 years for the municipality of Fislis. This hydrological data is available in the national “Banque Hydro” (http://www.hydro.eaufrance.fr/) database of hydrological measurements. The hydrological analyses were performed on a series of maximal data on daily discharges using the “Hydrological Frequency Analysis” software, HYFRAN® (INRS Canada). Six distribution functions often used to analyse flood frequencies were applied (Xu and Booij, 2007; Merz and

Thieken, 2005; Haktanir, 1992): GEV (Generalised Extreme Value), GP (Generalised Pareto), GUM (Gumbel), PE3 (Pearson type 3), LN3 (Lognormal 3-parameter-type) and EXP (Exponential). The calculation of confidence intervals was performed with the HYFRAN® software using the "parametric bootstrap" method (Fortin et al., 1997). The four statistical distribution methods judged representative of a probable reality (GEV, GUM, PE3 and LN3) were tested in the two case studies, in order to reveal the model uncertainties. A confidence interval of 90% was used to take into account the parametric uncertainties of the models. The results of the hydrological analyses in terms of discharges for different probabilities of occurrence (return periods) are shown in the following graphs (Figure 2). The central, minimum and maximum values (CI = 90%) related to eight different return periods were used to perform the different sensitivity tests (5, 10, 20, 30, 50, 100, 200 and 500-yr).

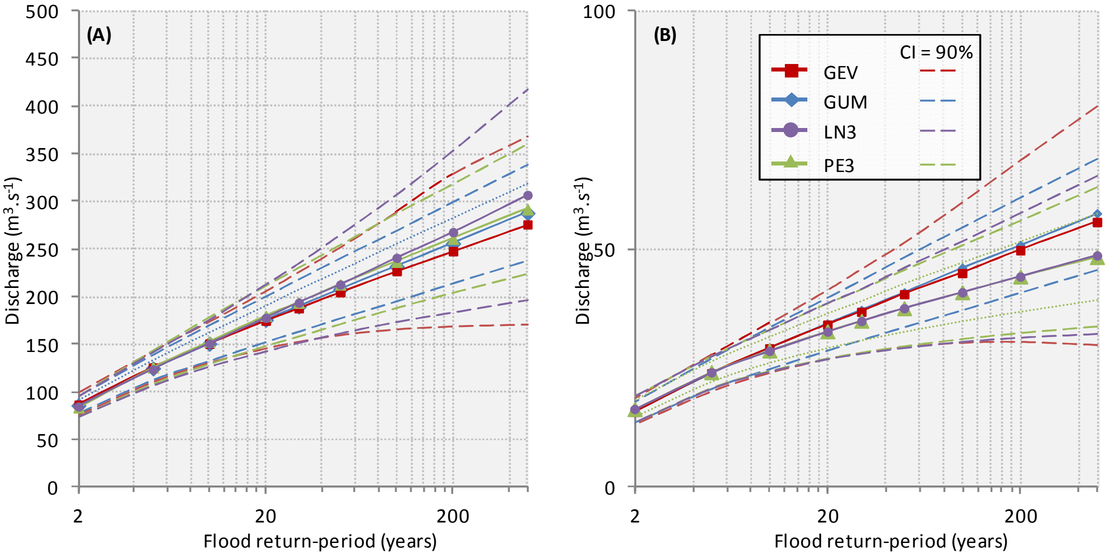

Figure 2: Results of hydrological analyses. The case of Holtzheim on the left (A) & Fislis on the right (B).

### 2.2.2 "Hydraulic" module: flood simulation and mapping

Several hydraulic models were developed in the framework of this study. For the municipality of Holtzheim, we used as basis: a hydraulic model designed by the engineering office DHI between 2005 and 2008 at the request of the Urban Community of Strasbourg, with the hybrid 1D/2D software (1D-2D) MIKE Flood®; and topographical data obtained using the Light Detection and Ranging (LIDAR) technique with 1 point per $m^2$, with an altimetric precision of 10 cm. For the second case study, an existing model designed by the General Council of Haut Rhin (French institution) with the 1D HEC-RAS® software and a numerical model with a resolution similar to that of Holtzheim were used. These tools formed the foundations of the different models developed in the two case studies. The different modelling strategies adopted for the "hydraulic" module were based on the type of hydraulic modelling software used (model uncertainty identification) and methodological simplifications/considerations adopted when building the topology of the models (parametric uncertainty identification). Other authors have also considered these aspects in a different way (Apel et al., 2008a; Merz and Thieken, 2009; Cook and Merwade, 2009). In this study, we used three hydraulic software applications and three different levels of detail were considered when building each model, with reference made to three scales of analysis (micro, meso and macro) (Table 1). The following table summarizes all the different strategies developed (Table 2).

The two-dimensional parts of the 2D and 1D-2D models were built with a grid of square rectangles of homogenous size. The method of bathymetric interpolation developed by Merwade et al. (2008) was used to complete the bathymetric information of the 1D models and supply better description of the main channel for 2D models. All the scenarios considered the main hydraulic obstructions as a function of the scale of analysis adopted. In all, 18 models were built and analysed in this study. We simulated and mapped floods with return periods of 5, 10, 20, 30, 50, 100, 200 and 500-yr.

Table 2: Differences between the strategies of the “hydraulic” module of the flood risk assessment with respect to the different types of hydraulic modelling software and simplifications performed.

| **Type of hydraulic modelling software (approach)** | **Methodological simplification/considerations** |
|---|---|
| 1D software HEC-RAS 4.1[a]. Representations of main river channels and floodplains by lines and cross-sections. | Number and position of cross sections; number of hydraulic singularities modelled. |
| 2D software MIKE21[b]. Representation of main river channels and floodplains by a digital elevation model (DEM). | Size of 2D grid cells; number of hydraulic singularities modelled. |
| Hybrid 1D/2D software MIKE Flood[b]. Representation of the river main channel by lines and the floodplain by a DEM. | Number of cross-sections and singularities concerning the 1D part of the model. Size of grid cells concerning the 2D part of the model. |

(a) Software developed by USACE (United States Army Corps of Engineers). Site WEB: www.hec.usace.army.mil/software/hec-ras/
(b) Software developed by the engineering office DHI Group. Site WEB: www.mikebydhi.com/Products/WaterResources/

### 2.2.3 “Vulnerability” module: classification and characterisation of assets

Two groups of building characteristics were needed to characterise building vulnerability: (1) construction characteristics, *i.e.* the height of the first floor, presence of a basement; and (2) occupation characteristics, *i.e.* type of occupation, type of activity, localisation of the activity in the building and the real rate of occupation. Several databases with different levels of precision can be used to identify these different aspects of the vulnerability of a territory. Three existing databases (DB) were used here to extract the building occupation characteristics for both study sites:

- the BD TOPO® database designed by the French National Institute of Geography (IGN), uses numerical information (geo-referenced data) on land use and morphology at a scale of 1 :25 000. The database includes a geographic information system (GIS) “buildings” layer that contains the spatial representation of the contours of buildings with tabular descriptions of types of use (residential, commercial, etc).

- the BD OCS database describes land use in homogenous areas according to 94 classes at a scale of 1:25 000. This database was built at the request of the Alsace Region;

- local databases composed of GIS layers with geo-referenced points indicating the addresses of buildings were enhanced with information drawn from other local databases (Chambers of Commerce/Industry and local municipalities) with reference to the types of activity of the buildings. These databases were much more complete for the case of Holtzheim than for that of Fislis.

Complementary methods were implemented to make up for the limitations of these databases. First, interviews were conducted with local real estate experts to determine construction characteristics, *e.g.* presence of basements, height of first floor. Second, three types of field survey were performed on both case studies: (1) a superficial field survey, called “S Survey”, in order to identify the average characteristics of all the buildings of the municipalities; (2) a semi-in-depth field survey called “SID Survey” in order to estimate the average characteristics of buildings by homogenous area of land-uses, pre-identified by map analyses; and (3) an in-depth survey called “ID Survey”, in order to identify and measure the characteristics in an elementary scale, building by building. Six strategies concerning the “vulnerability” module, based on these different databases were used to characterise the vulnerability of buildings in the two case studies (Table 3). These strategies were also based on different scales of analysis: the level of precision of the strategies developed increased from Approach A ("macro" scale) to Approach F ("micro" scale).

The variability of risk assessment results induced by these approaches reveals model uncertainties in the estimations. To take into account the uncertainties linked to considerations on the data measured, estimated and determined by expert opinion, *i.e.* parametric uncertainties, we determined the MIN-MAX uncertainty boundaries according to the study by Paté-Cornell (1996). Two supplementary scenarios were considered for each approach: the MIN and MAX scenario, corresponding to the combination of uncertainties on data resulting in a minimum and maximum estimation of the vulnerability of buildings. Thus, 18 vulnerability assessment approaches were performed for each case study.

Table 3: The data and considerations taken into account in the different strategies concerning the "vulnerability" module, used to characterise the vulnerability of buildings.

| | **Approach A** | **Approach B** | **Approach C** | **Approach D** | **Approach E** | **Approach F** |
|---|---|---|---|---|---|---|
| **Source of data** | BD TOPO | BD TOPO<br>BD OCS | BD TOPO<br>BD OCS<br>Local DB | BD TOPO<br>BD OCS<br>Local DB<br>S Survey | BD TOPO<br>BD OCS<br>Local DB<br>SID Survey | BD TOPO<br>BD OCS<br>Local DB<br>ID Survey |
| **Presence of basement** | Expert opinion | Expert opinion | Expert opinion | Average values | Average values | Identified individually |
| **Height of first floor** | Expert opinion | Expert opinion | Expert opinion | Average values | Average values | Measured individually |
| **Rate of occupation of ground floor** | Expert opinion | Expert opinion | Estimated | Estimated | Average values | Estimated individually |

### 2.2.4 "Damage" module: damage functions and asset values

Two groups of damage functions frequently used in the French context to assess potential flood damage to residential buildings were used in this study. The first set of damage functions used "Model 1" was developed by Torterotot (1993) while the second set, "Model 2" was developed for several municipalities in the Ile-de-France Region (at the end of the 1980s) (D4E, 2007), and reused in the framework of the standard cost/benefit analysis tool for flood management purposes of the "Plan Rhone" in 2010 (Ledoux Consultants, 2010). These two sets of damage functions distinguish buildings with and without basements. They represent the potential damage index of residential buildings as a function of submersion height in relation to the first floor of buildings (water depth) (Figure 3).

In order to calibrate these damage functions, it is necessary to determine the average value of the dwelling by $m^2$ and the surface area of buildings exposed to floods. The total projected area of the buildings and their spatial localisation were identified in the same way for the different scenarios of analysis, using the BD TOPO® database. This method was also the source of diverse uncertainties. A comparison of the areas of 155 buildings in the zone of Holtzheim obtained from the BD TOPO® database with areas extracted from orthophotos highlighted that this database overestimated the areas of buildings by 5% (Eleutério, 2008). The construction value of the buildings was estimated using the opinion of real estate experts. A standard deviation of 25% of the value estimated in comparison to the average was observed between the minimum and maximum values estimated according to expert opinion. In addition to these uncertainties, the damage coefficients proposed above (Figure 3) are themselves marked by uncertainties (D4E, 2007). Damage functions associated with error margins and explanations concerning the existing level of uncertainty are rare, making this estimation difficult. All these cumulated uncertainties were considered in this study as sources of parametric uncertainties and assessed theoretically. We considered that the damage coefficients used in our tests could have an uncertainty of ± 30%. The monetization of direct damage to economic activities was performed with existing damage functions (DNRM , 2002) for the different assessment scenarios. Given that this typology of building represents the minority of buildings in the municipalities analysed, these functions were not subjected to the uncertainty tests performed in our work.

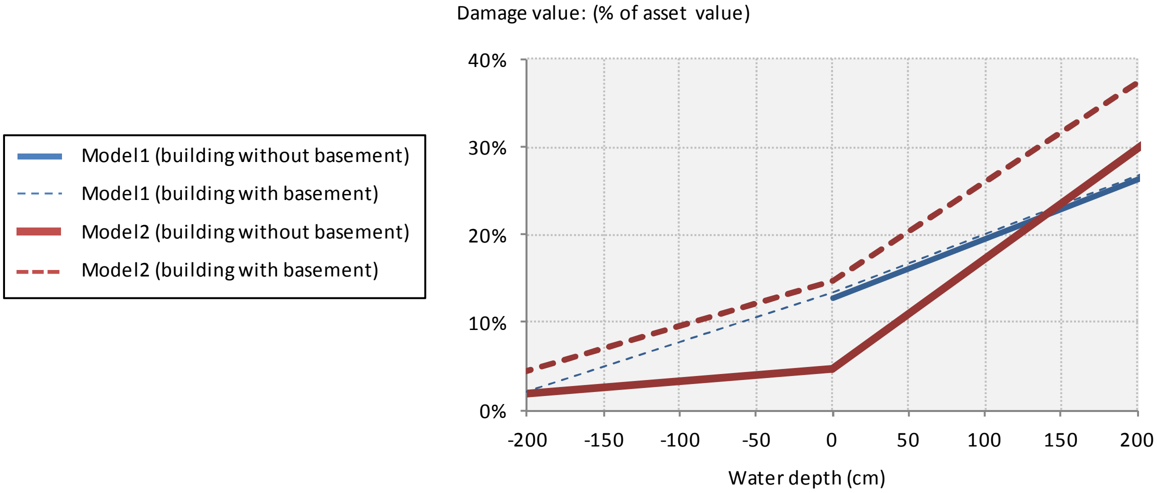

Figure 3: Different damage functions used in the sensitivity tests for the “damage” module.

### 2.3 Propagation of uncertainties

The combination of different data and the calculation of damage and average annual costs of damage, *i.e.* expected annual damage (EAD), were done using F.R.A.GIS GIS-based tool, developed for this purpose (Eleutério et al., 2010). Each analysis strategy of the different modules gave rise to a risk estimation. The number of scenarios implemented to analyse the impact of each assessment module on the damage estimates are presented in Table 4. In addition to these assessment scenarios, we considered nine others for each case study in order to take into account the impact of scales in the assessment results. The total of 65 damage assessment scenarios was implemented for each case study. Each scenario comprised damage assessments for eight floods, with return-periods equal to 5, 10, 20, 30, 50, 100, 200 and 500-yr, and the calculation of EAD. The quantification of the variability of these damage estimates is presented in the following section.

Table 4: Number of damage assessment scenarios implemented for each case study to analyse the impact of epistemic uncertainties of each assessment module in risk estimations.

| Assessment modules | Holtzheim | Fislis |
|---|---|---|
| Hydrology | 12 scenarios | 12 scenarios |
| Hydraulics | 18 scenarios | 18 scenarios |
| Vulnerability | 18 scenarios | 18 scenarios |
| Damage | 8 scenarios | 8 scenarios |

## 3. RESULTS

### 3.1 Global uncertainty of assessments

The risk curves (damage/frequency) were obtained as a function of the strategic choices made for the different assessment modules, according to the combinatory method proposed (Figure 1). The minimum and maximum boundaries of these curves are shown in the following graphs (Figure 4).

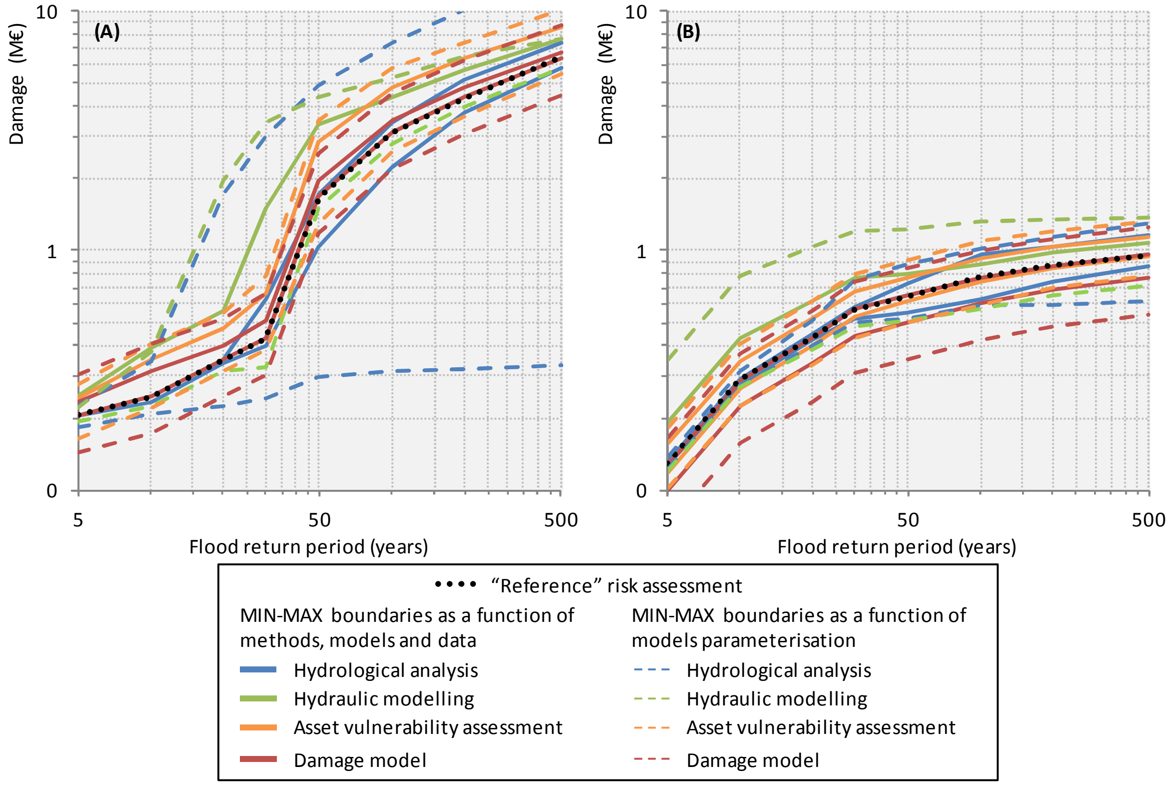

Figure 4: Damage potential for different flood return-periods as a function of model and parametric uncertainties. The case of Holtzheim on the left (A) and that of Fislis on the right (B).

The flood risk proved to be very different for the two municipalities analysed. By analysing the "reference" scenario, we observed that the first flooding events were likely to cause damage of the same order of magnitude for the two study sites. Few stakes were exposed to flooding for small return-period flood events. However, for the municipality of Holtzheim, the progression of damage was relatively slow for events of high frequency since the town centre is protected against floods by a dike (return-periods less than around 30 years, shown in graph A of Figure 4). Whereas for the municipality of Fislis, the damage increased significantly for these high frequency events (graph B of Figure 4). We also observed that the variability of the results due to the selection of models, methods and data was less marked when adding the uncertainties linked to their parameterisation (parametric uncertainties). The following graphs allow clearer understanding of the results by highlighting the role of each assessment module in the variation of risk estimations. These graphs represent the minimum and maximum boundaries in comparison to the values obtained with the "reference" assessment as a function of the methods, models and data (Figure 5), and as a function of the parameterisation of the models (Figure 6).

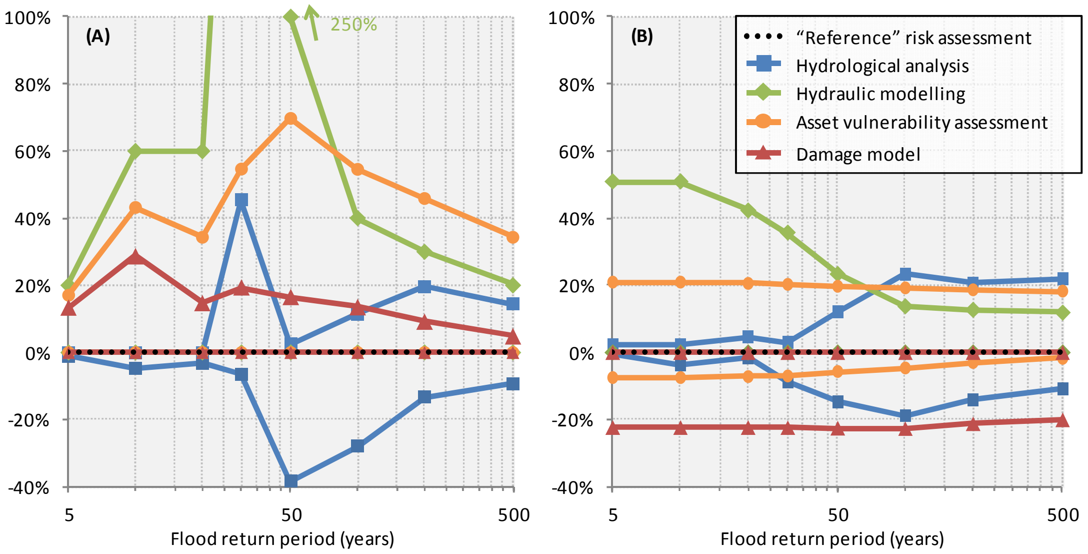

Figure 5: Variation of damage estimates in comparison to the results of the "reference" assessment – as a function of the methods, models and data. Holtzheim on the left (A) and Fislis on the right (B).

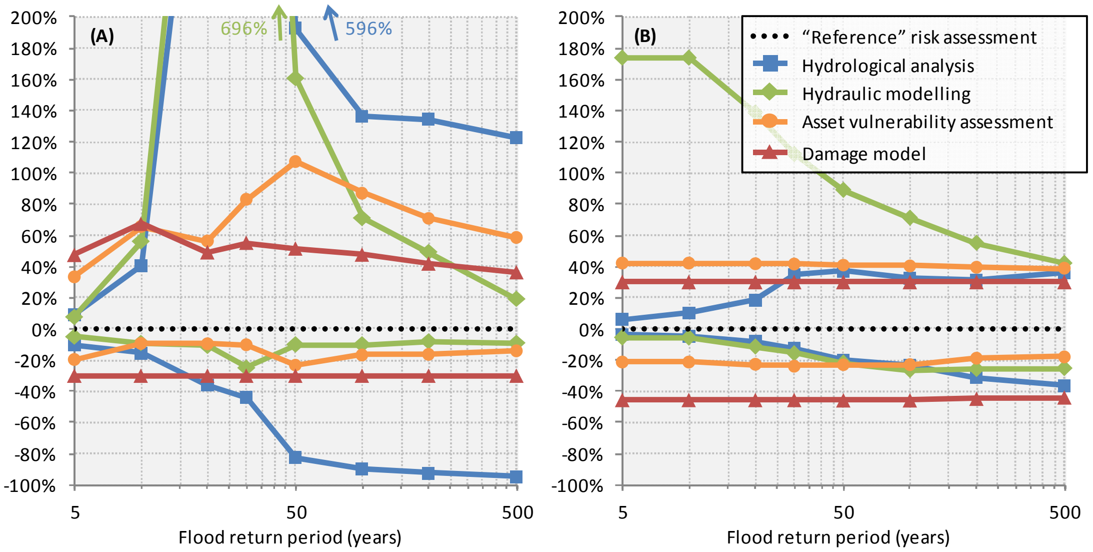

Figure 6: Variation of damage estimates in comparison to the results of the "reference" assessment - as a function of the parameterisation of the models. Holtzheim on the left (A) and Fislis on the right (B).

The peaks shown in the case of Holtzheim (graph A in Figure 5) highlight a particularity of this site due to the existence of a flood protection dike. The difficulty of certain modelling scenarios to represent this structure led to considerable variability in determining the return-period of failure of the structure. In the case of Fislis (graph B in Figure 5), hydraulic uncertainty was observed mainly for frequent floods, for which small overestimations of water heights and areas covered by the flood hazard played a very important role in quantifying potential flood damage.

Although the order of magnitude of the uncertainties was much greater for the parametric uncertainties (Figure 6), the similitude between these two figures (Figure 5 and Figure 6) reveals that the parametric uncertainties propagate in a very similar way to that of uncertainties linked to models, methods and data.

However, we observed a huge difference concerning the hydrological module (graph A in Figure 6). The impact of taking into account the confidence intervals of 0.9 was very significant for the case of Holtzheim. This was also due to the hydraulic structure present on this study site. The following graphs (Figure 7) represent the variations induced by these different sensitivity tests carried out in terms of expected annual damage (EAD).

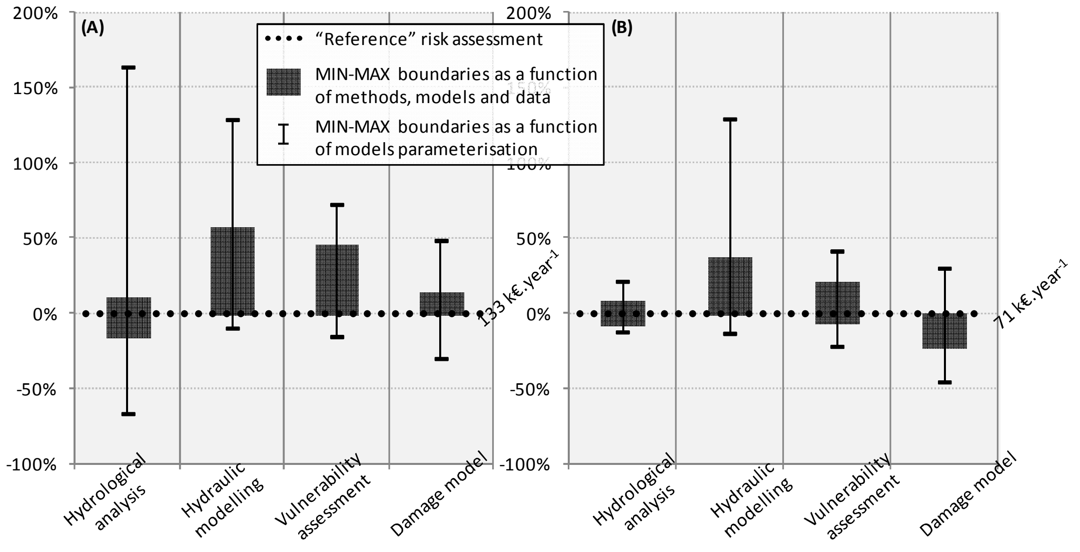

Figure 7: Expected annual damage and uncertainty bounds as a function of methods, models, data and parameterisation of the models. The case of Holtzheim on the left (A) and that of Fislis on the right (B).

We observed that the variability of EAD due to the selection of methods, models and data (model uncertainties) was very similar for the two case studies. The hydraulic modelling was the most important factor in the variability of estimates, followed by the characterisation of the the vulnerability of assets. The amplitudes (MAX-MIN) of the uncertainty boundaries relating to the "hydraulic" module were 25% (Holtzheim) and 43% (Fislis) greater than those related to the "vulnerability" module. There was a difference regarding the roles of hydrology and the damage functions. In the case of Holtzheim (graph A in Figure 7), the selection of hydrological functions played a greater role than the selection of the damage model. The amplitudes induced by the "hydrology" and "damage" modules correspond to 56% and 31% respectively of the amplitude induced by the "vulnerability" module. In the case of Fislis, these amplitudes were relatively higher corresponding to 54% and 83% respectively (graph B in Figure 7). This can be explained by the fact that in the second case study buildings without basements predominated and that the heights of the water flooding the site for events of greater frequency were relatively low. In this case, the difference between the two damage models used (damage functions) is greatest (*cf.* Figure 3).

The major difference between the two case studies concerns the variability of the EAD due to simplifications/considerations taken into account during the analysis (parametric uncertainties). In the case of Holtzheim (graph A in Figure 7), we observed the strong influence of hydrological considerations (confidence intervals of 0.9) and the parameterisation of hydrological models. It is noteworthy that the sensitivity tests concerning parametric uncertainties performed on the "hydrology" module indicated strong potential for both under overestimating EAD. The MIN-MAX boundaries of these tests (graph A of Figure 4) demonstrate how the flood protection structure of Holtzheim influenced this module, *e.g.* the minimal assessment scenario was caused by the non-failure of the protection structure due to the underestimation of water stream height generated by hydrological considerations. At Fislis (graph B in Figure 7), we observed a very weak influence of hydrological considerations on the EAD. The uncertainty linked to the parameterisation of hydraulic models remained strong, though not as strong as that of the other case study. It appears that the uncertainties mostly generated overestimations of potential direct damage.

### 3.2 Discussion on the results

All the tests performed revealed a general tendency of overestimating flood direct damage potential to buildings. The tests at different scales of analysis of hazard and vulnerability demonstrated the strong influence of these considerations on the assessment results by pointing out the precise role of one module or the other as a source of uncertainty. In the two case studies, the larger the scale of assessment, the higher the estimated damage values for both the hazard modelling and the method to assess the vulnerability of assets. The uncertainty compensation mechanism proved very complex to analyse. The variability of the results due to the selection of methods, models and data were very similar between the two case studies. Regarding the latter, hydraulic modelling was the most important factor in estimate variability, followed by the assets characterisation approaches. The uncertainties linked to flood models tended to under/overestimate risk through the generalised increase or reduction of water heights and flooded surfaces. On the contrary, the uncertainties linked to the characterisation of asset vulnerability were subjected to spatial variability, liable to be the source of a compensatory effect when summing up the overall potential flood damage, *e.g.* the underestimation of the first-floor height of a building can be offset by the overestimation of this characteristic for other buildings. The main differences between the results of the two case studies were observed when performing the tests relating to parametric uncertainties, *i.e.* uncertainties linked to different considerations and data introduced in the models. The determination of the hydrological confidence intervals and the uncertainties related to the processing of topographical and bathymetric data in the hydraulic models was crucially important for the first case study (Holtzheim). The flood protection dike at the site in question was the main source of these differences. On the one hand, the variation of the failure return-period of the structure was a very sensitive parameter for the assessment. On the other hand, certain hydraulic simplifications eliminated the detailed inclusion of this structure in the calculation, leading to an overestimation of the damage caused by floods of greater frequency. These particularities linked to the sites highlight the complexity of studying uncertainties in deterministic approaches. Other results concerning scale influences are showed in the thesis of Eleutério (2012).

## 4. CONCLUSIONS AND OUTLOOK

This work showed, firstly, that the uncertainty of each module of the assessment (hydrology analysis, hydraulic modelling, vulnerability assessment and damage models) depends on several factors that are highly dependent on the characteristics of the sites studied. The role played by flood hazard modelling was preponderant in assessing flood risk to buildings, especially for the most frequent floods. This showed that great attention must be given when modelling frequent floods for damage assessment purposes. The results of this study showed that taking protection structures (dikes and dams) on a site into account is an important factor in decisions involving the accuracy of the probability analysis. This aspect proved to be a significant source of uncertainty in the damage assessment process. Furthermore, this work showed that scale-considerations played a non-negligible role in the risk assessments. Larger scales led to considerable overestimation of damage in comparison to smaller scales. These results show that in-depth consideration is required prior to using flood maps and vulnerability databases in view to assessing potential flood damage.

The degree of subsisting uncertainty in these assessments leads us to reflect on existing uncertainties at a second level of assessment (networks and their effects). Uncertainties linked to the identification of hazard still require integrating the risks of structure failure and climatic change (hydrological probability). The vulnerability of a territory also depends on networks, infrastructures and crisis management systems. The complexity of these aspects of risk leads to other still more complex levels of uncertainty when assessing indirect and intangible damage. The weight of existing uncertainties in quantifying risk calls into question the use of this sole criterion as a support for decision-making. Standardised methods that take into account uncertainties would be an efficient mean of using these tools in a comparative manner. In spite of the existence of different uncertainties, these assessments are extremely powerful tools for understanding flood risk. Consolidating these assessments remains a path for further research, as does flood risk management for which the scope of analysis should be widened to include the social and political dimensions of this risk.

## 5. REFERENCES

Apel, H., Aronica, G., Kreibich, H., and Thieken, A.: Flood risk analyses - how detailed do we need to be?, Natural Hazards, 49, 79-98, 10.1007/s11069-008-9277-8, 2008a.

Cook, A., and Merwade, V.: Effect of topographic data, geometric configuration and modeling approach on flood inundation mapping, Journal of Hydrology, 377, 131-142, 2009.

D4E: Évaluations socio-économiques des instruments de prévention des inondations, Paris, 117, 2007.

de Blois, C. J., and Wind, H. G.: Assessment of flood damages and benefits of remedial actions: "What are the weak links?"; with application to the loire, Physics and Chemistry of the Earth, 20, 491-495, 1995.

DNRM (Department of Natural Resources and Mines, Queensland Government): Guidance on the assessment of tangible flood damages, Brisbane, Australia, 21, 2002.

Eleutério, J., Payraudeau, S., and Rozan, A.: Sensibilité de l’évaluation des dommages associés aux inondations en fonction de la caractéristique de la vulnérabilité des bâtiments, Ingénieries EAT, 55-56, 29-44, 2008.

Eleutério, J., Martinez, D., and Rozan, A.: Developing a gis tool to assess potential damage of future floods, Risk Analysis VII, Algarve, Portugal, 2010,

Eleutério J., Flood risk analysis: impact of uncertainty in hazard modelling and vulnerability assessments on damage estimations, PhD thesis, University of Strasbourg, FR, 243pp., 2012.

Green, C., Viavattene, C., and Thompson, P.: Guidance for assessing flood losses: Conhaz report, Flood Hazard Research Centre – Middlesex UniversityWP06, 80, 2011.

Ledoux Consultants: Guide d'accompagnement pour une méthode standard pour l’analyse coût / bénéfice des projets de prévention des inondations, Mission Rhône (DREAL Rhône-Alpes / Service Prévention des Risques), 2010.

Merz, B., Kreibich, H., Schwarze, R., and Thieken, A.: Review article "Assessment of economic flood damage", Natural Hazards and Earth System Sciences, 10, 1697-1724, 10.5194/nhess-10-1697-2010, 2010b.

Merz, B., Elmer, F., and Thieken, A. H.: Significance of 'high probability/low damage' versus 'low probability/high damage' flood events, Natural Hazards and Earth System Sciences, 9, 1033-1046, 2009.

Merwade, V., Cook, A., and Coonrod, J.: Gis techniques for creating river terrain models for hydrodynamic modeling and flood inundation mapping, Environmental Modelling & Software, 23, 1300-1311, DOI 10.1016/j.envsoft.2008.03.005, 2008.

Messner, F., Penning-Rowsell, E., Green, C., Meyer, V., Tunstall, S., and van der Veen, A.: Evaluating flood damages: Guidance and recommendations on principles and methods, FLOODsite Consortium, Wallingford, 179, 2007.

Paté-Cornell, M. E.: Uncertainties in risk analysis: Six levels of treatment, Reliability Engineering & System Safety, 54, 95-111, 1996.

Torterotot, J. P.: Le coût des dommages dûs aux inondations: Estimation et analyse des incertitudes, CERGRENE, Ecole Nationale des Ponts et Chaussées, Paris, 634 pp., 1993.